Linear Signatures in Urban SAR Images - Partly Misinterpreted?

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Abstract

Corner lines, line signatures related to building facades in SAR images, are commonly related to signal double reflections, either specular or diffuse. However, the scene properties - building orientation, building shape, surface roughness - often do not correspond to this expectation. This paper presents a 3D representative simulation case study, based on ray tracing and a detailed facade model, in order to analyze the origin of corner lines at facades. The simulation results indicate that the intensity of corner lines may be dominated by signal triple reflections of different type.

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Index Terms

SAR simulation, urban, persistent scatterer interferometry, signal reflection, TerraSAR-X

I. Introduction

In urban SAR imagery, point-like and line signatures are the main sources of information for building extraction and monitoring. Isolated bright pixels are of major interest for interferometric methods exploiting SAR data stacks, e.g. persistent scatterer interferometry (PSI) [1] or tomographic SAR (TomoSAR) [2]. Line signatures support methods for building reconstruction based on radargrammetry [3] or multi-aspect SAR [4], [5]. In this context, different line detectors are used for identifying building facades such as the Tupin detector [6], the Steger detector [7] or the standard Hough transform [8]. Moreover, changes between two SAR images are detected for urban areas based on the comparison of linear structures [9].

Line signatures in SAR images related to the intersection of facade and ground - in the following referred to as corner lines - are often related to signal double reflections of specular or diffuse type. From the geometrical point

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Fig. 1: Test site for case study (Munich city center). Window arrangement repeats on every second floor level.

of view, specular double reflections primarily occur at facades oriented in line-of-flight of the sensor. Diffuse signal contributions depend on the surface roughness and are of relevance if the surface standard deviation is comparable to the signal wavelength. Radiometric models for describing these reflection effects assume canonical building shapes represented by box models, e.g. [10], [11].

However, these assumptions are not representative for urban areas. Many facades are not oriented in line-of-flight, excluding specular double reflections. Moreover, the surface roughness of ground and facade is often moderate or even negligible, weakening diffuse double reflections. Finally, the geometry of facades is often complex. Structural details such as windows or balconies interrupt the surface planarity, which is in disagreement with box model representations.

Interestingly, high resolution SAR images as acquired by TerraSAR-X [12] often reveal dominant corner lines representing facades with detailed structural elements. In this paper, a 3D simulation case study is conducted for the first time in order to investigate the origin of corner lines for that kind of buildings. The impact of facade structures on the appearance of corner lines is simulated. Based on that, consequences are discussed for 2D SAR algorithms (exploiting the SAR image geometry and radiometry) as well as for interferometric SAR methods, e.g. InSAR, PSI, TomoSAR.

II. Motivation

This work is enabled and motivated by three components elaborated at TUM: a 3D SAR simulator (RaySAR) focusing on object geometries, a very detailed facade model, and a stack of high resolution spotlight SAR data from TerraSAR-X used for PSI processing. Originally, the components have emerged from complementary efforts focused on SAR simulation methods for understanding signal reflection phenomena as well as on the evaluation

Fig. 2: Close up view on facade structures.

of PSI potentials (localization, monitoring of individual buildings). In this paper, the bundle propels extending the geometric analysis of corner lines published by Wegner et al. [13] which was supported by simulation methods of TUM [14]. The analysis of corner lines is extended at three crucial points:

- Analysis in 3D: simulating in 3D (azimuth, range, elevation) is necessary to link signal contributions to their physical origin. Moreover, in addition to conclusions in the azimuth-range plane, the impact on interferometric methods can be evaluated.
- Level of detail of the object model: the 3D geometry of facade structures is considered by the SAR simulator. This is fundamental as the majority of dominant signals backscattered from buildings is triggered by facade structures, e.g. more than 50 % of PS are situated at facades [15]. Certainly, these dominant signatures can be only confirmed by the simulated image if the geometry of the facade structures is represented by the 3D model. In [13], facades are only represented by flat surfaces in the building model.
- Corner reflections: Besides standard double reflection of diffuse type, further (optional) effects on the corner lines are revealed and discussed. TerraSAR-X images and results from PSI processing enable to confirm the presence and the impact of these effects.

For a simulation case study, a building test site has been chosen in the Munich city center. The conclusions drawn in the simulation context, however, are expected to be representative for many buildings. A general discussion in this regard is given in Section IV). The paper statements advice caution to researchers making assumptions on line signatures in SAR images of urban areas.

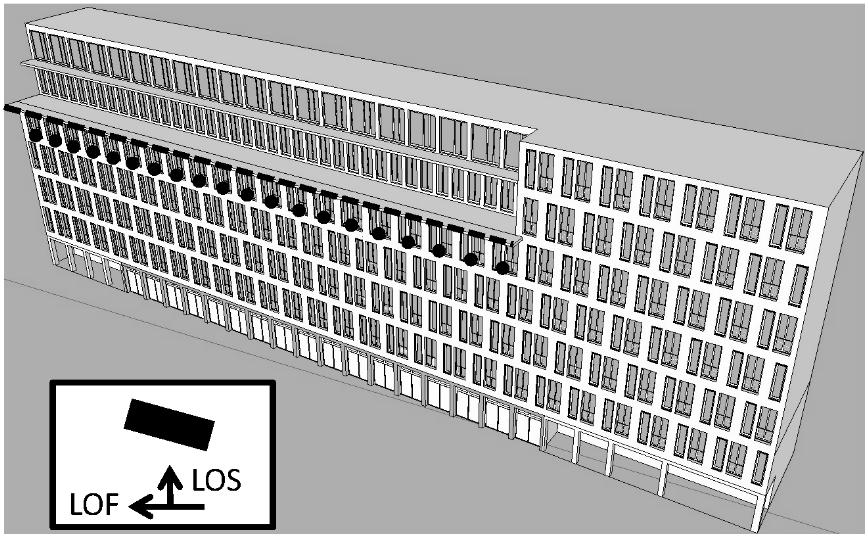


Fig. 3: Facade model. The image indicates the building orientation with respect to TerraSAR-X (box: top-down view showing line of flight LOF and line of sight LOS). The steep incidence angle leads to a row of hidden windows (dots) due to a balcony (dashed line); see simulation result in Section III-C.

Fig. 4: Model details.

III. Case study

A. Facade structure

Fig. 1 shows a general view on the building of interest. The facade is covered by window frames whose regular arrangement repeats on every second floor level. The spacing on the ground level is regular as well but different due to bigger glass surfaces (see Fig. 2 for details). The window frames are made of metallic material, favoring triple reflections at the window corners, and are partly covered by balcony structures. The brick wall and the ground in front of the building are characterized by little roughness (with except of a ground part covered with grass). A large balcony structure interrupts the upper half of the facade.

B. Modeling & Simulation

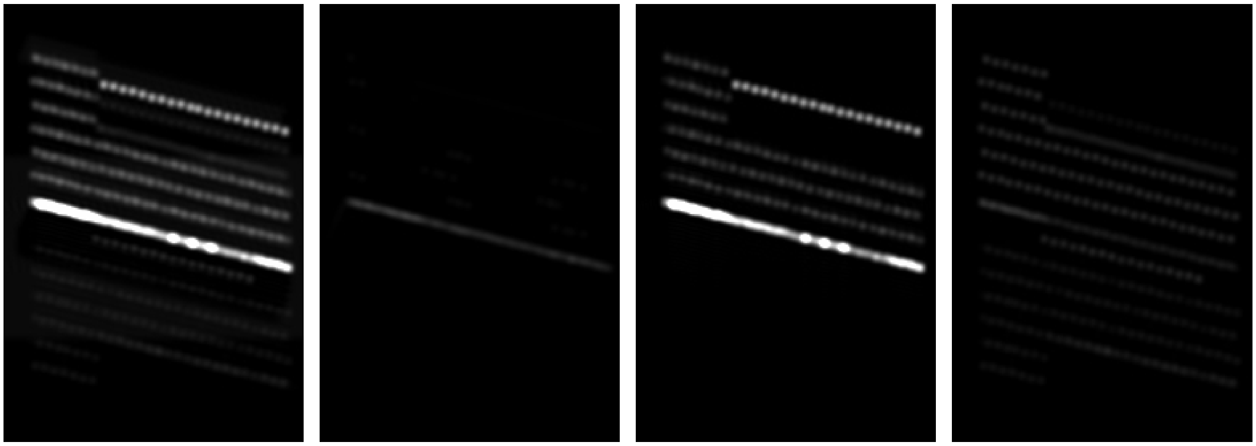
The 3D building model is created based on a photogrammetric survey (data source: stereoscopic overview and close-up images). After calculating 3D facade coordinates in ERDAS imagine, the 3D facade model is created with SketchUp, a Trimble software. As the focus of the paper is on the simulation results, the reader is referred to Auer et al. [16] for further details on the modeling step. The geometric accuracy of the facade model is 2-3 cm along all 3 coordinate axes. Fig. 3 gives a general overview of the model which represents details on the ground level (regular spacing, protrusions at both ends), the geometry of windows (framework, balconies; see Fig. 4), and the large balcony at the building top.

The simulation is conducted with RaySAR [14], a software developed at TUM, which provides the position of phase centers in 3D (azimuth, range, elevation). To this end, the scene model is adapted to the SAR imaging geometry (incidence angle: 22.62°, ascending orbit with heading angle: 346.46°). Fig. 3 indicates the building orientation with respect to the TerraSAR-X trajectory. The density of rays for sampling the model is 5 cm in azimuth and elevation (third axis: range for depth values). According to reality, the facade and ground surfaces are assigned with strong specular and weak diffuse reflectivity. Signal reflections at glassy surfaces (windows) are deactivated in the model. The impact of surfaces covered by grass is neglected in the model but is considered in the discussion of the simulation results.

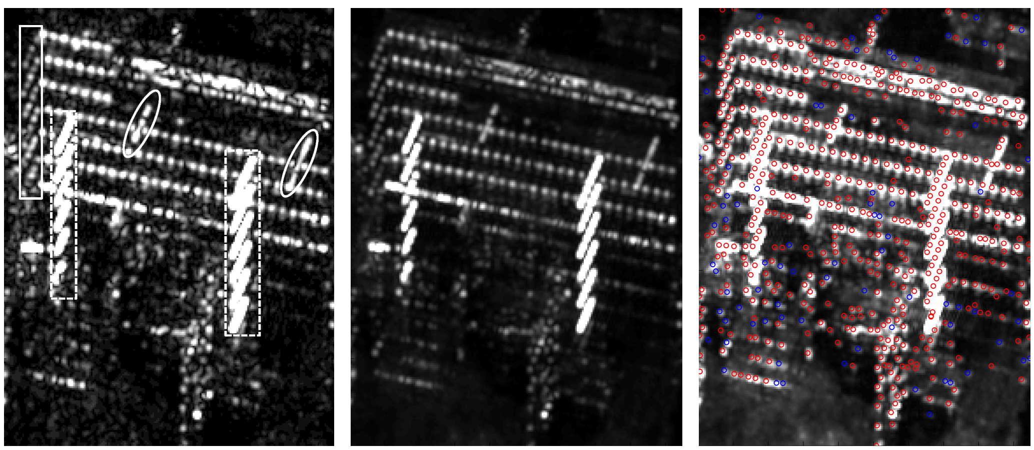
C. Simulation in the azimuth-range plane

For obtaining a SAR image, the discrete samples provided by the ray tracer are summed coherently within a pixel raster in azimuth and range. The spacing (0.43 m and 0.22 m) and the spatial resolution (1.1 m and 0.59 m) in azimuth and range are adapted to TerraSAR-X. The simulated images are shown at the top of Fig. 5 with one layer containing all signal contributions and separate layers for double, triple, and fivefold reflections (layers subsequently referred to as reflection levels 2, 3, and 5). Direct backscattering (due to low surface roughness) and fourfold reflected signals are negligible and, hence, are not shown in separate layers.

Starting with reflection level 2, diffuse signal contributions related to the dihedral facade-ground are condensed in a line (Fig. 5b). However, the intensity of the line is weak compared to the allover appearance of the building which



(a) Sum of all signals (b) Reflection level 2 (c) Reflection level 3 (d) Reflection level 5



(e) TerraSAR-X image (HR spotlight) (f) Average image (84 images in data stack) (g) Persistent Scatterers (red: final PS, blue: PS candidates)

Fig. 5: Simulation vs. TerraSAR-X (see building orientation in Fig. 3). Frames, ellipses: facade structures not represented by the building model, i.e. solid frame: adjacent facade, dotted frames: facades in the rear of the building, ellipses: roof railings of adjacent building parts. Azimuth (corresponding to line-of-flight): left-right, Range: top-down.

is shown in Fig. 5a. In contrast, triple reflections dominate (Fig. 5c). Six rows of point signatures are related to window corners (three long and three short ones). A look to reality reveals four long and two short rows of windows (see Fig. 1 and Fig. 3). The reason is that, due to the steep signal incidence angle, most window corners on the 5th floor are concealed by the balcony structure on the 6th floor. Interestingly, the corner line at the intersection facade/ground is dominated by signal triple reflections. The limited spatial resolution of the sensor leads to point signatures merged to a line (see corner line in Fig. 5c), which is much stronger than the line related to reflection level 2. Fivefold reflections, shown in Fig. 5d, are much weaker than triple reflections and are related to a mirror effect explained in [17], e.g. following the signal path antenna - ground - triple reflection at window corner - ground - sensor (corresponding to faint point signatures below corner line). The radiometric correctness of the simulated images is moderate due to the simplified reflection models inherent to RaySAR [14]. Especially, strong differences between the reflectivity of metallic (e.g. window frames) and non-metallic surfaces (e.g. ground) are considered but only roughly approximated.

The distribution of dominant signatures is confirmed by the TerraSAR-X images (Fig. 5e, Fig. 5f). The corners on the facade yield dots whereas the bottom end of the facade is represented by a corner line. Details of three facades and two roof railings are not represented by the 3D model. Fig. 5g confirms that most of the bright dots can be exploited as persistent scatterers. Obviously, the distribution of PS on the corner line is irregular in contrast to the distribution of facade PS. In addition, many bright pixels related to reflection level 5 are selected as PS candidates or even as PS.

As a conclusion, the corner line of the facade contains isolated (but smeared) corner reflections of reflection level 3 imposed on a weak (steady) line of diffuse double reflection. In the following section, the discrete 3D positions of the signal phase centers of reflection level 3 are analyzed in order to understand where the triple reflections originate from.

D. Simulation of 3D phase centers

For linking the signal contributions to the facade geometry, the phase center positions are projected to the facade model. Fig. 6 gives a close-up view on the facade (phase centers marked by dark cubes). Besides standard corner reflections at the windows, a row of phase centers is visible at the bottom end of the facade. The facade part shown in Fig. 6 indicates six physical corners on the ground level which may be related to six signal phase centers. However, the simulation reveals additional phase centers without correspondence to physically existent corners. The reason is related to the facade structure. Due to small protrusions at the windows, a significant part of the radar signal follows specular triple reflections, where the signal path is: antenna - (non glassy) window surface - window side - ground - sensor (visualized in Fig. 7). The resulting phase center is located on the ground level. The intensity pertinent to the phase center depends on the number of floors having the same window arrangement. That is, for the test site three windows frames, located on every second floor level, contribute to the same phase center on the ground. The multiplication effect is distinguishable in the simulated image (Fig. 5a) and in the TerraSAR-X average image (Fig. 5f), where on the left end a small part of the corner lines shows higher intensity than the rest of the line. Grassy ground parts will disturb this effect. However, the impact is expected to be almost negligible for the building at hand as signal reflections happen on ground parts narrow to the facade (steep signal incidence angle).

Extending the conclusion of the last section, the dominant part of the facade corner line is composed by regular corner reflections on the ground level and Signal triple reflections triggered by vertically oriented dihedrals on the facade.

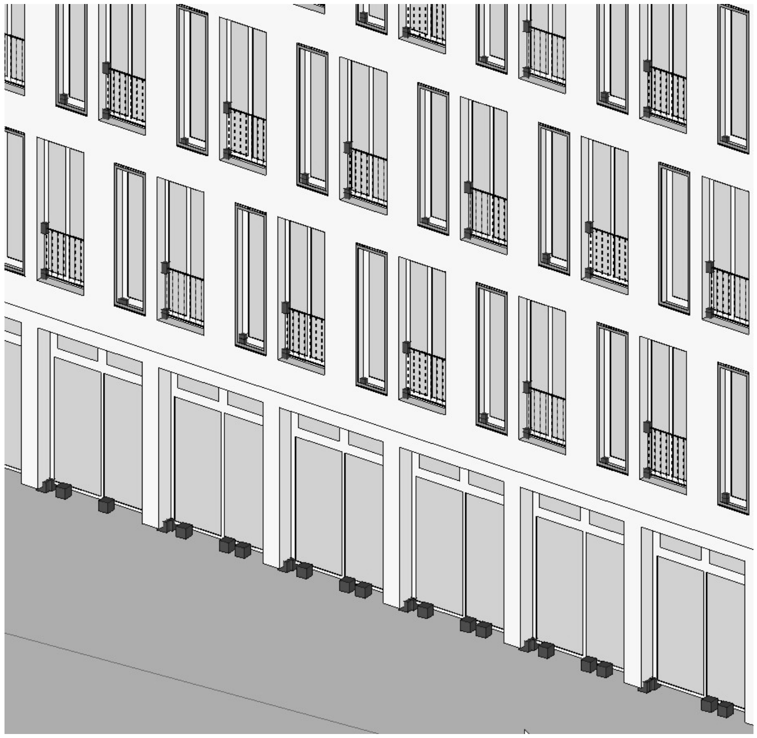


Fig. 6: Close-up view on 3D phase centers (marked by dark cubes). Phase centers are related to regular corner reflections on the ground level or locally at the facade. Additional signal phase centers, without correspondence to real existent structures, are localized on the ground and are related to signal interaction with dihedrals on the facade and the ground (signal path shown in 7).

IV. Discussion

The simulation facilitates our general understanding of corner lines as the scene setting may be representative for many urban scenes in SAR imaging, i.e. building not oriented in line-of-flight of the sensor, detailed facade structures, reflective surfaces, and surface standard deviations much smaller than the signal wavelength. The findings of the case study also apply for SAR systems of lower spatial resolution as the signal reflection effects are the same. As a difference, nearby signature rows may be merged with the corner line, resulting in a smearing of the line in range. Moreover, diffuse signal contributions may be more prominent due to the increased size of the resolution cell.

Corner lines of reflection level 2 are relevant, either specular or diffuse. However, in this context, specific pre-requisites have to be fulfilled with respect to the geometry and the surface characteristics. The simulation case study indicates that often signal triple reflections may be the dominant source of appearing corner lines. In this context, regular corners on the ground level and vertically arranged facade dihedrals play a key role. Both types of targets may respond constantly over a wide range of angles, the latter with the help of reflective ground in front of the facade. The related signal reflections depend on the depth of facade protrusions as well as on the signal incidence

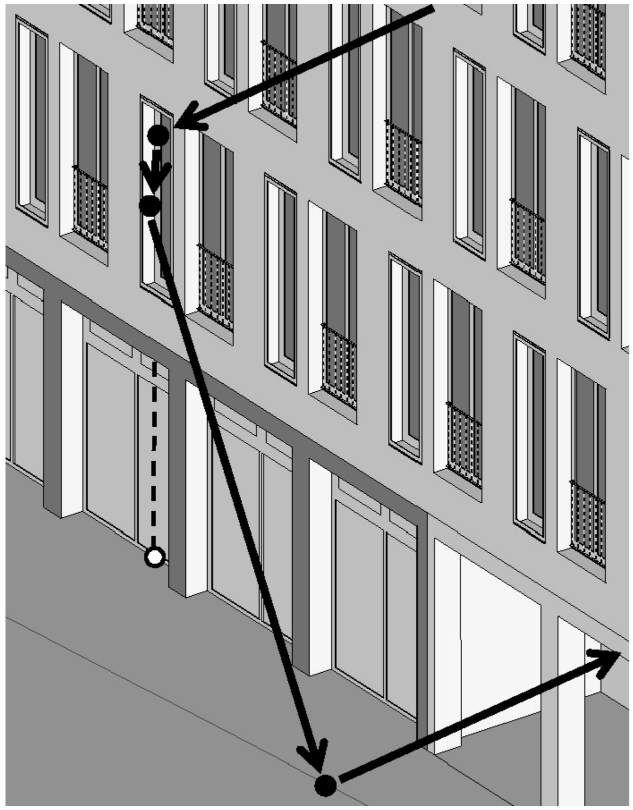


Fig. 7: Triple reflection of type facade-facade-ground (black dots). The 3D phase center of the corner is located at the bottom end of the facade (white dot).

angle (occlusions). For facades not oriented in line-of-flight, triple reflections of type facade dihedral/ground may lead to a corner line even if regular signal reflections are disabled, i.e. no diffuse signal double reflection due to negligible roughness and no physical corners on the ground level. Given a signature row of signal triple reflections, the following consequences are expected for SAR algorithms:

- Little impact is expected on geometric models for extracting building information as line detectors respond to rows of nearby point signatures, e.g. for identifying the position and orientation of facades. This is good news as facade ground lines are distinguishable for varying building orientations. However, the extraction of the length of line segments requires knowledge about the type of signal reflection. Lines of type diffuse double reflection tend to be slightly longer than the real extent of the facade (see [14], Chapter 5.1.2). In contrast, as shown in this paper, corner lines composed by triple reflections represent the distribution of trihedrals on the ground level or the arrangement of dihedrals on the facade. Both cases will lead to an underestimation of the facade length and to a shift in horizontal direction.

- Radiometric models, e.g. for extracting building heights from signal intensities, have to be kept flexible with respect to the type of signal reflection, i.e. double/triple reflections of specular/diffuse type. The development and selection of appropriate models is challenging as facade structures show strong variations. For instance, the identification of mixed double and triple reflections in corner lines may rely on the signal strength and standard deviation of the intensity along the corner line. Intensity peaks may then be used to estimate the extent of corner reflectors whereas line parts of lower but constant intensity may reveal the extent of the dihedral facade plane/ground.

- Interferometric SAR algorithms such as PSI and TomoSAR may suffer from mixed signal contributions in corner lines. As confirmed by the simulation case study, diffuse double reflections and/or different types of specular triple reflections may appear almost at the same 3D position. This problem is obvious in Fig. 5g, where the selection of PS based on the pixel amplitude does not follow any geometric rule. According to the simulation, the corner line contains a regularity which is smeared out due to the spatial resolution of TerraSAR-X. The signal phase of corner line pixels may contain deformations of the dihedral facade-ground, dihedrals all over the facade, and corner reflectors on the ground level.

V. Conclusion

The case study (facade in Munich city center) presented in this paper confirms that signal triple reflections at real or physically not existing corners can be the dominant source of facade corner lines in SAR images. This result extends the common understanding of corner lines which are often related to signal double reflections (diffuse, specular). For the first time, the contribution of signal triple reflections to the corner line has been simulated and discussed, supported by the comparison with spotlight TerraSAR-X data and PSI results. Based on the findings, the impact on algorithms for extracting building information has been indicated. The case study does not allow general statements on the composition of corner lines which depends on the scene properties (building orientation, facade details, surface roughness, materials). Nonetheless, the answer to the question in the paper title is: misinterpretations of corner lines at facades may occur if signal triple reflections are not taken into account.

VI. Acknowledgements

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